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MULTIDIMENSIONAL SIGNAL CODING IN THE VISUAL SYSTEM

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13. ABSTRACT (Maximum 200 words)

This work shows that units in the visual system are tuned to principal components
of real world color natural images and provides insight on the strategy the visual
system may be using to confront natural imagery. In addition, we developed an
efficient coding model for naural time varying imagery in the early visual system.

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AFOSR 91-0082
Multidimensional Signal Coding in the Visual System
Annual Technical Report Year One
(due date 11/30/91)

1.   SUMMARY

The aims of this research shortly recapitulated are:

(1)   To study the multidimensional spatio-temporo-chromatic signal processing capabilities of visual receptive fields

(2)   To identify the key attributes of multidimensional image signals which are sensitive to receptive field filters and how these attributes are transformed for encoding beyond the receptive fields.

Spatio-chromatic coding:

This work shows that units in the visual system are tuned to principal components of real world color natural images and provides insight on the strategy the visual system may be using to confront natural imagery. It is also useful for identifying image components that are significant for the visual system and those which it either keeps or enhances for later stages of signal representation and analysis. The methods by which retinal center/surround R/G type cells can be used to realize this coding system are also investigated.

Spatiotemporal coding:

In collaboration with NASA, the properties of a number of natural spatio-temporal sequences was measured. We found that the sequences showed regularity in both temporal and spatial domains. We found a spectrum model which represents .98 of the signal energy as separable. In addition, we developed an efficient coding model for natural time varying imagery in the early visual system. We show that M&P channels conjoin with tracking eye-movement to make visual system retinal architecture matched to basic components of time varying imagery.

Receptive field filtering:

A new method to analyze parallel and hierarchic processing was developed to account for how receptive fields in the visual system combine in terms of their anatomical convergence and divergence.

2.   STATUS OF THE RESEARCH

(i)   Spatio Chromatic Coding:

Neurophysiology provided color research with a wealth of single unit recordings indicating how color is coded in the early visual system. These show that when color is coded in the visual system it is encrypted together with spatial features. Filters (receptive fields) in the visual system have spatial responses with varying spatial frequencies which are modulated by different color (wavelength) profiles. Some combinations occur frequently in the visual system and some are rare or non-existent.

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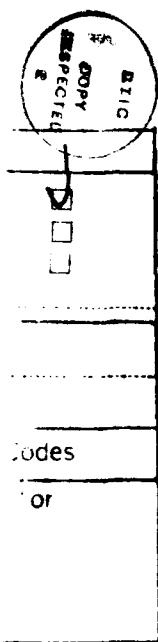
An obvious requirement of the coding system is that it be sufficient to contain all image information relevant to the visual system for processing at higher levels of the visual system. One of the most commonly applied hypotheses to understand the coding strategy is that the visual system is an efficient coder and that it is matched to its signal environment which is *natural color imagery*. By decomposing natural imagery to its building blocks we can compare how these are matched by the building blocks of the visual image coding scheme.

The principal components (eigenfunctions) of a group of signals can serve as a basis for that group. The advantages of representing a signal by principal components can be briefly summarized as follows. (i) The basis functions of the representation are orthogonal and have uncorrelated coefficients. (ii) The expected square coefficients (eigenvalues) are minimum compared to other generalized Fourier representations. These properties make principal components attractive for efficient signal coding and representation, because uncorrelatedness reduces redundancy and smaller coefficients require smaller dynamic ranges and hence, less transmission resources. Similar considerations have been used before in identifying the strategy of visual system operations. The eigenfunctions of black and white images are well-known. They include functions with periodic profiles in both spatial dimensions. We extended the analysis of the one-plane black and white images to 3-plane color images.

We computed the principal components of a number of natural color images using small sections of the images. We used 3-D blocks of 4 x 4 pixels in each color plane. The visual system also applies receptive fields which cover small sections of the image. Principal components computed for the natural color images are comprised of basis functions with various spatial and color profiles. These principal components are similar to certain visual system image operations in space and in color, including the color opponent transformation and a variety of spatially organized receptive field filters with different orientations. Color opponent profiles are most prominent in low spatial frequencies and have very low eigenvalues for high spatial frequencies. For example, the fraction of signal energy represented in low spatial frequency color profiles is significant, while the expected signal energy in color profiles with high spatial frequency is negligible. This suggests that color and space are nearly separable when small sections of natural images are considered. This separability diminishes as the size of the sections increase. Another advantage of the small sections is their computational load. The computational load associated with whole images or large sections thereof, in this kind of analysis, is immensely large. We reconstructed the image using the eigenfunctions. We find that the image can be reconstructed from a small number of eigenfunctions which are similar to visual system receptive fields.

(ii)   Spatio Temporal Coding:

We investigated the mechanisms and strategy used by the visual system to encode time varying imagery. The underlying hypothesis is that the early visual system efficiently codes natural time varying imagery. This is accomplished by combining tracking, implemented with smooth pursuit eye movements, to prefilter the image and shift the image spectrum into a low temporal frequency range and by matching retinal pathway characteristics to the properties of imagery after modification by tracking. We formulate a representation for time varying imagery which consists of two spatiotemporal components. The first component results from 3-D motion in the visual scene and is modeled as translational motion (a velocity field). The second component results from stationary (nontranslational) temporal changes such as flicker. We show, using sequences of natural imagery, that the spatiotemporal spectrum and other attributes of natural imagery markedly differ before and after tracking. In the region of

tracking, the temporal frequency bandwidth and velocity distribution of the translational component is diminished. With increasing eccentricity from the region of tracking, the temporal frequency bandwidth and velocity distribution broadens. On the other hand, the stationary component is unaffected by tracking. Comparison of the properties of the tracked imagery to those of retinal architecture suggests that M and P pathways logically divide the tracked image spectrum and each transmits different attributes of the image. A specialized retinal architecture with a high acuity fovea which fixates on the tracked region and a decreasing acuity with eccentricity also matches the properties of the tracked signal as they vary with eccentricity from the region of tracking.

(iii)   Receptive Field Filtering:

The term multirate filter bank (MRB) is used in the filtering literature to describe a group of filters with different sampling rates; these can be arranged both in parallel and in a hierarchy. The retina is, for all practical purposes, a multirate filter bank. We derived general conversions between equivalent parallel and hierarchic multirate filter banks as well as sufficient conditions for existence and uniqueness of the conversions.

Scaled Gaussian analysis multirate filter banks (MRBs) are analysis MRBs whose filters are Gaussians scaled differently in width and height. They are frequently employed in vision research as well as in image processing. We define generalized scaled Gaussian analysis MRBs for both parallel and hierarchic architectures and derive conversions between them. We calculate the number of multiplications, number of additions, and total number of filter coefficients for both architectures implemented in direct form and time varying filter implementation. Our results are for both one-dimensional MRBs and two-dimensional MRBs with separable filters. In all cases, as has been shown for particular MRBs, the parallel MRB requires considerably more multiplications, additions and filter coefficients than the equivalent hierarchic MRB. We are now applying this new theory to the retinal architecture using anatomical constraints.

PUBLICATIONS

1.   "The Spatio-temporal Spectrum of Time Varying Imagery", M.P. Eckert, G. Buchsbaum, A.B. Watson, IEEE Transactions on Pattern Analysis and Machine Intelligence, in revision.

2.   "Conversion Between Parallel and Hierarchic Architecture Analysis Multirate Filter Banks", B.S. Levitan and G. Buchsbaum. IEEE Transactions on Signal Processing, accepted.

3.   "Efficient Coding of Natural Time Varying Imagery in the Early Visual System", M.P. Eckert and G. Buchsbaum. To be submitted within the next few weeks to Proc. R. Soc. (London).

4.   "Complexity and Filter Memory Requirements in Scaled Gaussian Hierarchic and Parallel Multirate Filter Banks", B.S. Levitan and G. Buchsbaum, submitted, J. Visual Communication and Image Representation.

5.   "Spatio-Chromatic Decomposition of Natural Images by the Visual System" (tentative title), J.B. Derrico and G. Buchsbaum.

6. "Retinal Architecture as a Multirate Filter Bank" (tentative title), B. Levitan and G. Buchsbaum.

ADVANCED DEGREES AWARDED OR PLANNED

M.P. Eckert, Ph.D. "Spatio-Temporal Image Coding in the Visual System" (tentative title), expected 1992.

B.S. Levitan, Ph.D. "Direct Computation and Hierarchic Processing in the Adaptive Expanded Retina", expected 1992.

OTHER PARTICIPATING PERSONNEL

Dr. Peter Sterling (retinal anatomy), Department of Anatomy, University of Pennsylvania.

Dr. Leif H. Finkel, Neural Networks Laboratory, Department of Bioengineering, University of Pennsylvania.

Dr. Andrew B. Watson, NASA, (spatio-temporal coding).

COUPLING ACTIVITIES/CONFERENCES

1. National Research Council Committee on Vision, Workshop on Visual Factors of Electronic Image Communication, Woods Hole, MA, "The Relationship Between Space and Color in Natural Images" (1991).

2. National Research Council Committee on Vision, Workshop on Visual Factors of Electronic Image Communication, Woods Hole, MA, "The Significance of Eye Movements and Image Accelaration for Coding Television Imagery" M.P. Eckert and G. Buchsbaum, prepared for publication of the workshop.

3. "M and P Cells Are Matched to the Spatio-temporal Image Spectrum Modified by Eye Movements", M.P. Eckert and G. Buchsbaum, 63rd Annual Meeting of the Association for Research in Vision and Ophthalmology. Invest. Ophthal. Vis. Sci. 32, 841 (1991).

4. "Efficient Image Coding Operations in Space and Color and Their Correlates in the Early Visual System", J.B. Derrico and G. Buchsbaum, 63rd Annual Meeting of the Association for Research in Vision and Ophthalmology. Invest. Ophthal. Vis. Sci. 32, 841 (1991).

5. "Decomposition of Natural Images by Principal Components as a Design Consideration for the Visual System", G. Buchsbaum and J.B. Derrico. Annual Meeting of the Optical Society of America (1991).

6. "The Basic Building Blocks of Color Vision: A Generalized View of the Opponent Color Transformation", G. Buchsbaum. Topical meeting on Advances in Color Vision, OSA (1992).

LECTURES

University of Rochester, Center for Visual Sciences, Rochester, NY, "Spatio-Chromatic Transformations in Vision" (1990).

McGill University, Center for Vision, "Decomposition of Natural Images by Principal Components as a Design Principle for the Visual System" (1991).

OTHER AIR FORCE LABORATORY

I have met with Dr. Mark Cannon from Patterson Wright at the OSA meeting to discuss research interests and future interactions.